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RE TR 71-36

CONDUCTIVE HEAT-TRANSFER RESISTANCE OF COMPOUND BARREL INTERFACE

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AUG 27 1971

TECHNICAL REPORT

Darrel M. Thomsen
and
Alexis B. Zavoico, CPT, U. S. Army

June 1971

RESEARCH DIRECTORATE

WEAPONS LABORATORY AT ROCK ISLAND

RESEARCH, DEVELOPMENT AND ENGINEERING DIRECTORATE

U. S. ARMY WEAPONS COMMAND

47

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Weapons Command Research, Dev. and Eng. Directorate Rock Island, Illinois 61201	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

CONDUCTIVE HEAT-TRANSFER RESISTANCE OF COMPOUND BARREL INTERFACE (U)

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Darrel M. Thomsen and Alexis B. Zavoico, CPT, U. S. Army

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1971	47	0

8a. CONTRACT OR GRANT NO. b. PROJECT NO. DA 1T061101A91A c. AMS Code 501A.11.844 d.	9a. ORIGINATOR'S REPORT NUMBER(S) RE TR 71-36 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release, distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Army Weapons Command

13. ABSTRACT

This is a continuation of a heat-transfer investigation performed as In-House Laboratory Independent Research to determine the effect of interface thermal-resistance on multilayer gun barrel radial temperature distributions. In previous Technical Reports 69-121 and 70-155, published under the same title, the task of establishing the feasibility of induced interface-resistance was discussed. During this reporting period, heat-transfer analysis and experimental correlation were continued. An experimental M60 gun barrel was fabricated and tested. The reduced outside barrel temperatures, of this firing test, demonstrated the effect of interface thermal resistance. Also, a significant effort was directed toward establishing fabrication techniques for a full-length thermal interface barrel. As a result of these efforts, a patent application has been submitted by the Research Directorate, Weapons Laboratory at Rock Island to cover this concept. (U) (D. Thomsen and A. Zavoico)

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Thermal interface resistance						
2. Heat transfer (conduction)						
3. Multilayer gun barrel						
4. Ceramics						

Unclassified
Security Classification

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OBJECTIVE

The objective of this analysis was to analytically and experimentally determine the effect of interface thermal resistance on multilayer gun barrel temperature distributions. Specifically, analysis was to be conducted to establish the design criteria for an experimental test barrel. Then, based on experimental correlation and additional analysis, design requirements were to be determined for a full-length modified gun barrel with consideration of the interfacial material requirements and forming processes.

INTRODUCTION

Consistent with an overall effort to increase weapon-firepower, this heat transfer analysis performed by the Research Directorate, Weapons Laboratory at Rock Island has been directed toward reducing gun barrel heat-transfer. Previous investigations under this subject, have been directed toward the preliminary task of analytically and experimentally substantiating the influence of induced-interface thermal resistance, and of measuring interface thermal resistance for various interfacial conditions.

The current investigation was coupled with previous analysis to establish design criteria for a full-length composite gun barrel with induced interface resistance. An M60, 7.62mm gun barrel was designed, fabricated and both analytically and experimentally evaluated.

A comprehensive study was undertaken to evaluate various fabrication techniques for gun barrels with full-length thermal-resistance interfaces. As part of this study, a material survey was performed to establish the most promising interface materials. Parameters considered in this survey included thermal conductivity, material stress properties, and thermal coefficient of expansion. The various barrel-forming techniques evaluated included co-extrusion, swaging, and shrink-fit. Guidelines were established for future fabrication of full-length modified gun barrels.

Acknowledgment is extended to the Metallic Materials Application Team and to the Process Technology Application Team, both of the Research Directorate, Weapons Laboratory at Rock Island for their contributions and guidance in the establishment of multilayer gun-barrel-forming criteria and in the application of interface material coatings.

ANALYTICAL AND EXPERIMENTAL INVESTIGATION

Heat Transfer Analysis

As part of the effort to establish design criteria for a full-length thermal interface gun barrel, analysis was performed on an M60 gun barrel to calculate temperature distribution as a function of induced interface thermal resistance. A gun barrel with a configuration, as shown in Figure 1, was analyzed to predict radial temperature distributions in the modified section of the gun barrel.

Experimental time-temperature history data for a standard M60 gun barrel was used to calculate effective propellant gas convection coefficients and gas temperatures. For the condition in which all heat is dissipated in the gun barrel or in which heat input by convection is equal to the change in barrel internal energy, the governing expression is:

$$h_g A[T_g - T] = \rho c_p \Delta r A_m \frac{dT}{d\theta}$$

where h_g = propellant gas convection coefficient

T_g = propellant gas temperature

A = bore surface area

A_m = mean surface area

T = gun barrel temperature

Δr = wall thickness

ρ = gun barrel material density

C_p = specific heat of gun barrel material

$\frac{dT}{d\theta}$ = rate of change of gun barrel temperatures with respect to time.

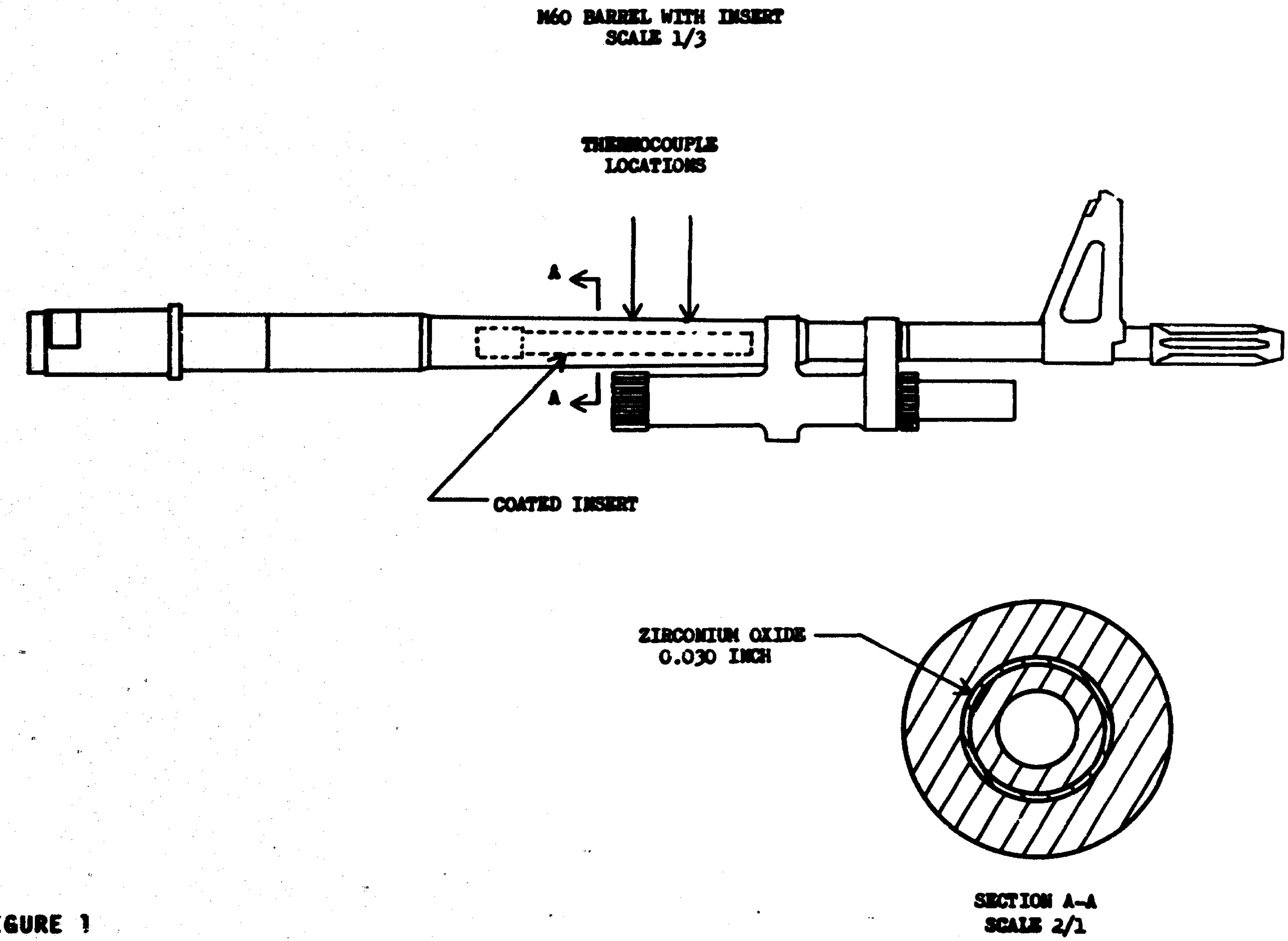

M60 BARREL WITH INSERT
SCALE 1/3
THERMOCOUPLE LOCATIONS
A
A
COATED INSERT
ZIRCONIUM OXIDE
0.030 INCH
SECTION A-A
SCALE 2/1

FIGURE 1

As the outside barrel temperature increases, dissipation to the surrounding environment must be accounted for in the equation. Heat transfer by radiation and convection is added to the equation and the solution for h_g and T_g follows by the same procedure. A typical computer program, based on the equation given above, for the calculation of effective propellant gas convection coefficients and temperatures is given in Appendix A.

Knowing effective propellant gas temperatures and convection coefficients, radial gun barrel temperatures (as a function of rounds fired) can be calculated for composite gun barrels with induced interface resistance. A computer program in which a Crank-Nicolson algorithm is used was employed for this purpose. A copy of this program is given in Appendix B. Results of these calculations are shown in Figure 4.

Based on the induced interface thermal resistance requirements determined by this analysis, an M60 gun barrel was modified by the insertion of a Zirconium Oxide (ZrO_2) coated section as shown in Figure 1. The various fabrication and assembly drawings for this modified gun barrel are shown in Appendix C. Detailed steps involved in the fabrication of the insert section and in the application of the ZrO_2 coating are shown in Figure 2. This was the first attempt to shrink-fit an outer sleeve over a ZrO_2 coating. Results of this effort were applied in the fabrication investigation of a full-length modified gun barrel discussed later in this report.

Experimental Results

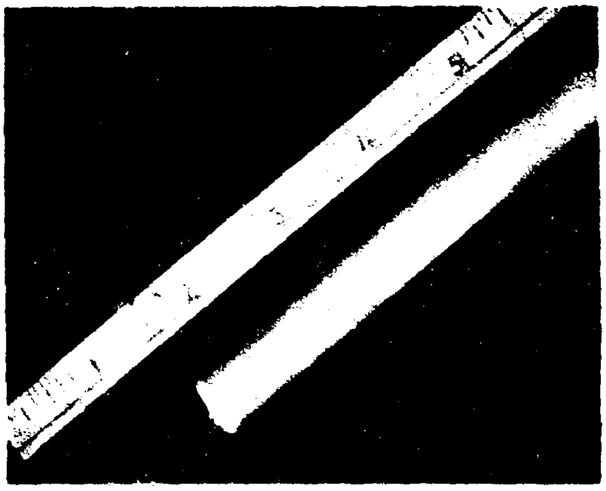
The modified M60 gun barrel of Figure 1, along with a standard barrel, was instrumented with thermocouples for a live-firing experiment to compare barrel temperatures and as an experimental correlation of the theoretical analysis. This experiment consisted of continuous automatic fire of 400 rounds at a firing rate of 600 rounds per minute.

Results of this firing experiment are presented in Figures 3 and 4. External gun barrel temperatures are plotted for two axial locations, 11.2 and 12.2 inches from the breech, both located within the modified section of the gun barrel. Both standard and modified measured gun barrel temperatures at the 12.2-inch location are given in Figure 3; whereas, both standard and modified measured gun barrel temperatures at the 11.2 location, along with calculated temperatures for this location are compared in Figure 4.

Barrel Segment as Received
Surface Preparation 44
Threads/Inch OD = .512"

Bond Coat Applied Nickel Aluminide
Composite #450
A Metco, Inc. Product OD = .528"

Zirconium Oxide Applied Over
Bond Coat
OD = .612"



Coated Liner Ground to Fit C140299
OD = .588"

FIGURE 2

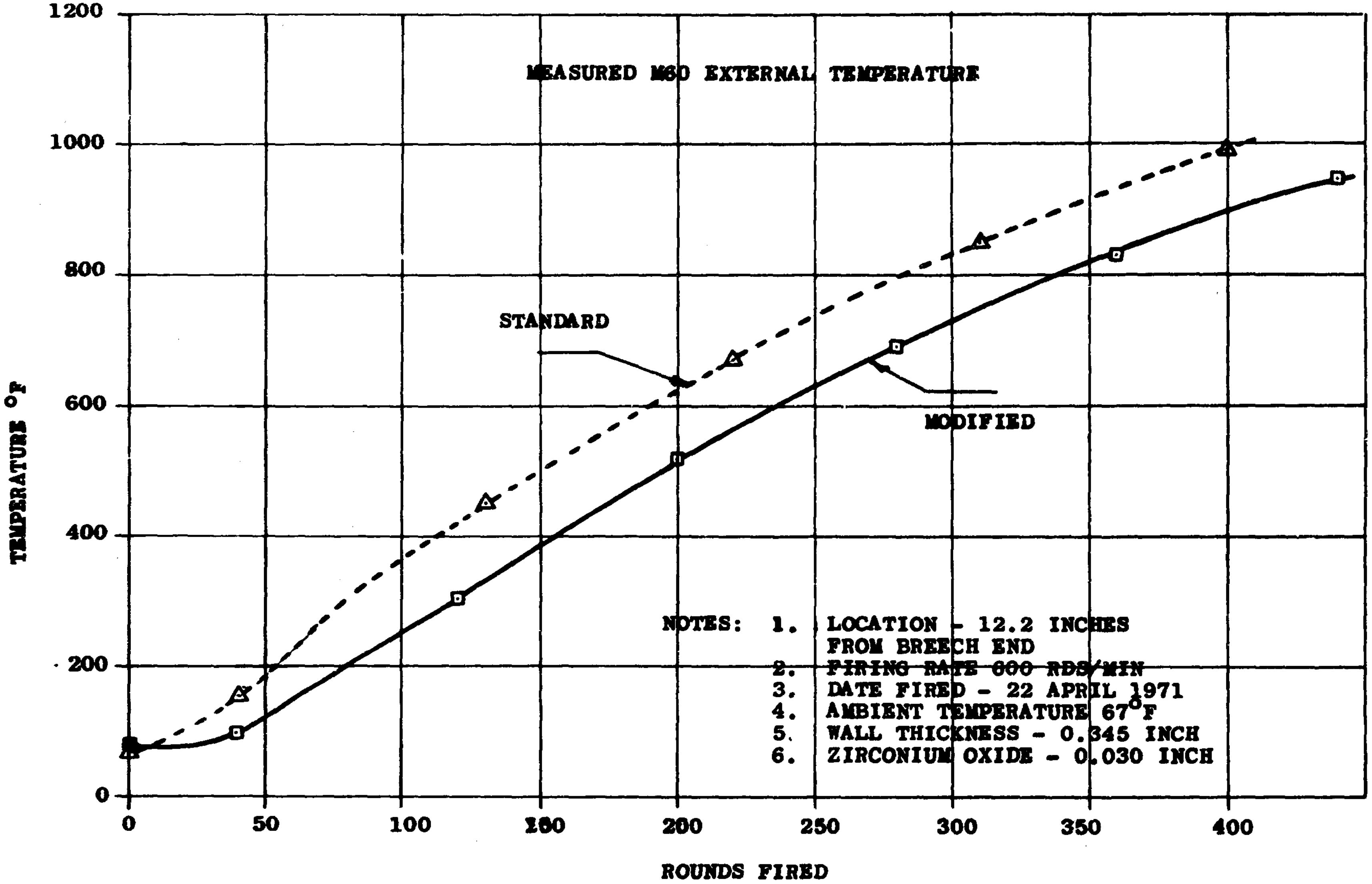

MEASURED M60 EXTERNAL TEMPERATURE
TEMPERATURE °F
1200
1000
800
600
400
200
0
0
50
100
150
200
250
300
350
400
ROUNDS FIRED
STANDARD
MODIFIED
NOTES: 1. LOCATION - 12.2 INCHES FROM BREECH END
2. FIRING RATE 600 RDS/MIN
3. DATE FIRED - 22 APRIL 1971
4. AMBIENT TEMPERATURE 67°F
5. WALL THICKNESS - 0.345 INCH
6. ZIRCONIUM OXIDE - 0.030 INCH

FIGURE 3

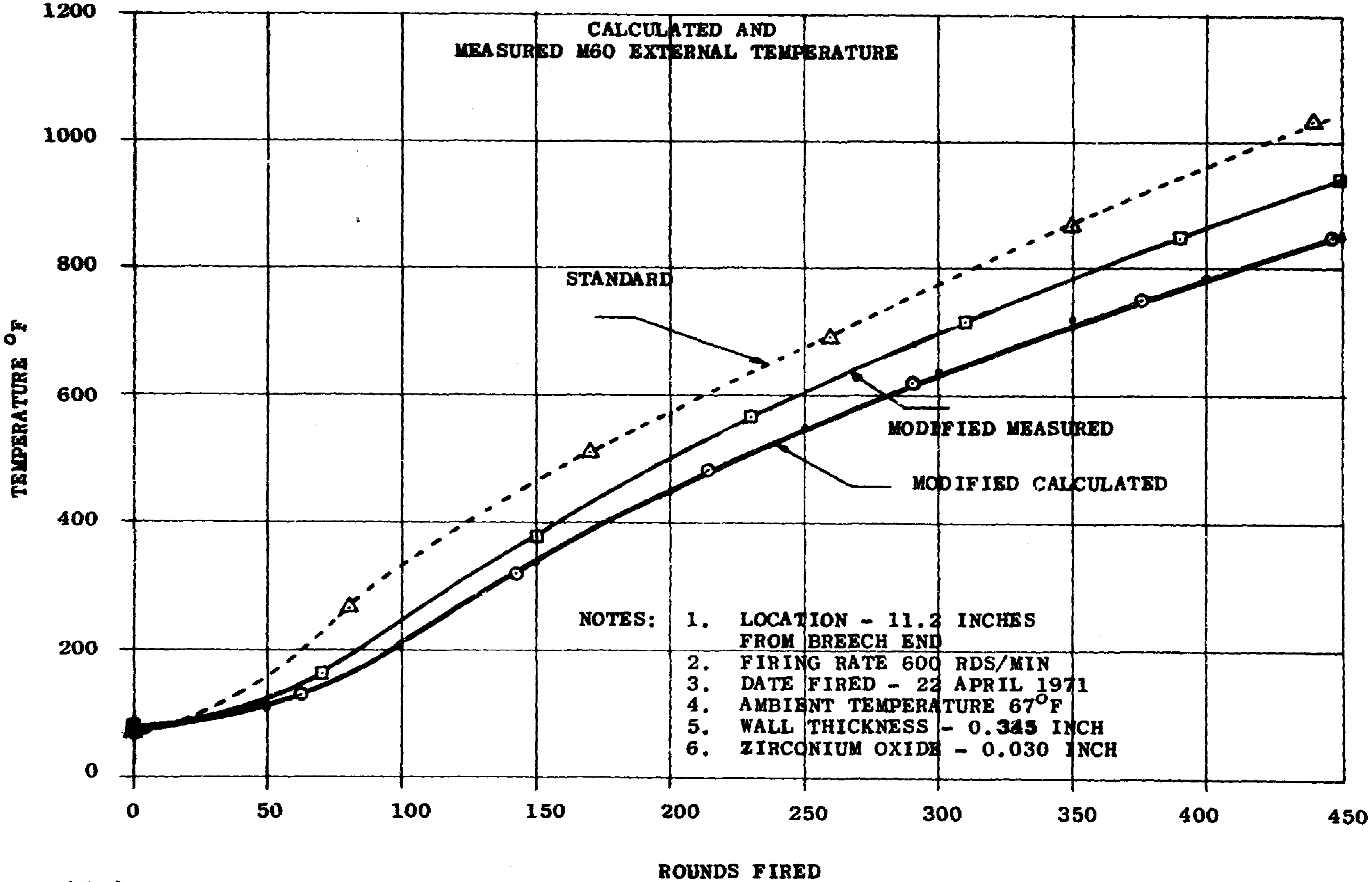

CALCULATED AND
MEASURED M60 EXTERNAL TEMPERATURE
STANDARD
MODIFIED MEASURED
MODIFIED CALCULATED
NOTES: 1. LOCATION - 11.2 INCHES FROM BREECH END
2. FIRING RATE 600 RDS/MIN
3. DATE FIRED - 22 APRIL 1971
4. AMBIENT TEMPERATURE 67°F
5. WALL THICKNESS - 0.345 INCH
6. ZIRCONIUM OXIDE - 0.030 INCH
TEMPERATURE °F
1200
1000
800
600
400
200
0
0
50
100
150
200
250
300
350
400
450
ROUNDS FIRED

FIGURE 4

The modified section operated at approximately 100°F cooler after 400 rounds than the same location on a standard gun barrel. Also, calculated temperatures, shown in Figure 4, are lower than those measured. This can be accounted for because the axial heat conduction into the specimen was neglected in the calculations. A significant amount of heat is transferred from the higher temperature, unmodified section into the modified section. Hence, a full-length modified gun barrel would operate at lower temperatures than measured, that is, at temperatures closer to those of the analytical calculations.

INVESTIGATION OF FABRICATION TECHNIQUES FOR MULTILAYER GUN BARRELS WITH INDUCED INTERFACE THERMAL RESISTANCE

The investigation of fabrication techniques for multilayer gun barrels with induced thermal resistance was subdivided into two interrelated subtasks - material selection and forming processes. Material properties will be partially altered by the forming process; furthermore, because of the limited number of low thermal conductivity materials, the number of forming processes available is limited by material properties.

Interface Material Selection

Various ceramics and other materials have been investigated for application in the fabrication of a full-length thermal interface gun barrel. High-temperature resistant materials with the low-thermal conductivity (less than 1 BTU/hr ft °F) required for a thermal barrier typically exhibit low tensile and shock strength properties. Normally, plastic deformation is absent prior to mechanical failure. With these property limitations in mind, two design approaches have been taken to obtain a mechanically stable barrier. First, the material can be a load-carrying member, solid configuration, capable of withstanding hoop stresses, thermal stresses, and axial shear stresses present during normal firing. Secondly, the material can be required to transmit loads to the outer sleeve that functions as a support for the entire assembly.

Based on these design requirements, thermal-material selection criteria have been established as follows:

1. Material must have low-thermal conductivity (less than 1 BTU/hr ft °F).

2. Material must be chemically and metallurgically stable, up to 3000°F. That is, no chemical or metallurgical reactions occur, such as material phase change or carbiding of other composite materials.

3. Material should have high-thermal shock resistance to preclude material breakdown during repeated thermal cycling (primarily for the solid configuration assemblies).

4. Interfacial material must have a linear coefficient of thermal expansion (CTE) similar to that of the barrel materials (Cr-Mo-V steel, a typical barrel material having a CTE of 7.8×10^{-6} in/in °F). Any CTE mismatch can result in failure in both the axial and the radial directions because of assembly separation during thermal cycling.

5. Interface material must be capable of sustaining or transmitting all modes of barrel loading.

The two most promising interface materials that closely satisfy these criteria are zirconium oxide (ZrO_2) and anisotropic boron pyrolytic graphite (bPG). Because of the different nature of these two materials, they will be discussed separately.

Zirconium Oxide

Zirconium oxide (ZrO_2), dependent upon the manufacture of the basic oxide and the coating process, varies in mechanical and thermal properties. Material density (percentage of porosity), degree of stabilizing agent employed (MgO, CaO prevent material phase-change throughout the operational temperature range), and degree of metallic alloying are the primary causes of these property variances. ZrO_2 may be found in various commercial forms, some of which are as follows:

1. Powders - applicable for flame-spraying.

2. Free-standing ceramic bodies (for example, extruded or pressed parts).

3. Tapes, papers, and fabrics.

A tabulation of typical thermal and mechanical properties for a sintered ZrO_2 (flame spray, partial stabilization) is as follows:

1. Thermal conductivity - .541 BTU/hr ft °F

2. Density - 374 Lb_m/Ft^3

3. Linear coefficient of thermal expansion
   5.6×10^{-6} in/in °F (RT to 2200°F)

4. Specific heat 0.13-0.18 BTU/Lb_m °F at 200 to 1950°F

5. Ultimate tensile strength (psi)

21,120	at	RT
15,000		1625°F
13,230		1886°F
12,000		2192°F

6. Ultimate compressive strength (psi)

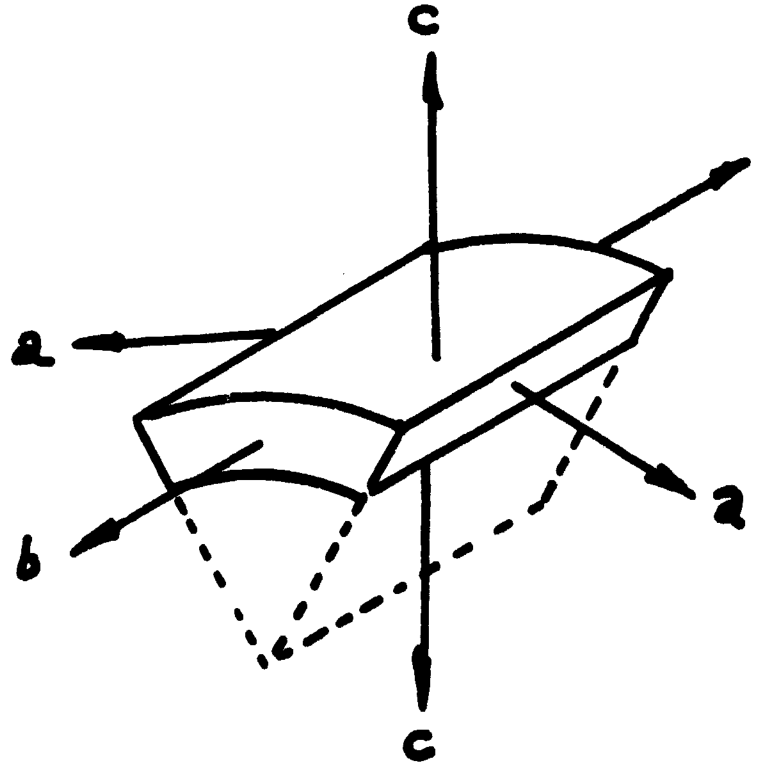
303,000	at	RT
100,000		2370°F

For a load-sustaining assembly (solid material configuration), the ceramic material must maintain its structural integrity. Therefore, the material mechanical properties must be sufficient to withstand all stress modes. Initial stress calculations with a homogeneous barrel assembly indicate that material failure will occur unless a precompressive stressing of the interface material can be obtained. For example, a gas pressure of 65,000 psi will cause a tensile stress at the interface in excess of 25,000 psi that exceeds the ultimate tensile strength of ZrO_2. Also, uneven axial loading can be a source of interface-material cracking. Experimental verification of assembly structural integrity must be performed to determine the significance of cracking.

In a load transmission assembly, ZrO_2 is required during forming to compress to a highly compacted, dense powder. During actual firing, no further compaction or shifting of the material is allowed. The assembly procedure necessary to obtain maximum compactions and proper natural flow will be determined experimentally in the future.

<u>Anisotropic Boron Pyrolytic Graphite (bPG)</u>

Boron pyrolytic graphite (bPG) exhibits strong anisotropy (different property values along different axes) in thermal and mechanical properties. This material is manufactured by a high-temperature, vapor-deposition process; therefore, it occurs only as a free-standing body configuration. The diagram below indicates the primary property directions for a radial element:



Radial Element

Anisotropy is exhibited in only two directions of a cylindrical coordinate system. The "c" property direction lies on the radial component and the "ab" property direction is a surface comprising the circumference and the axial axis. For use as an interface material, the "c" direction is the controlling direction. The alloying of basic pyrolytic graphite with boron (0 to 1.2%) results in alteration of material properties in both the "ab" and "c" directions. A percentage increase in boron causes a decrease in thermal conductivity, a major advantage for this application.

A material property compilation is presented in Table I for a zero percentage boron content:

TABLE I

Property	Direction c	Direction ab	Units
Ultimate Tensile Strength (RT)	1,500	14,000	psi
Ultimate Flexural Strength (RT)	1,500	21,000	psi
Ultimate Compressive Strength (RT)	68,000	14,000	psi
Thermal Conductivity (RT)	1.00	200	BTU/hr °F ft
(2500°F)	0.66	58	
Specific Heat (RT)	0.26		BTU/Lb_m °F
Linear Coefficient of Thermal Expansion	10.8	0.2	in/in °F X 10^{-6}

Thermal conductivity data are given in Table II for the "c" direction as a function of the percentage of boron alloying:

TABLE II

Per Cent, Boron	Thermal Conductivity BTU/hr ft °F
1.2	0.36
0.75	0.45
0.35	0.54
0	1.00

Mechanical properties are unavailable for boron alloying. Theory indicates that alloying will increase strength properties.

Application of bPG as an interface material is feasible for a solid configuration. Some work has been done with co-extrusion of isotropic graphite materials. The difficulty encountered was that isotropic graphite did not deform plastically during extrusion; therefore, composite failure occurred.

A deterrent factor in applying bPG as an interface material involves the mismatch of linear coefficients of thermal expansion (CTE). A comparison of bPG material with typical barrel materials indicates that, both in the "c" direction and on "ab" surface, the CTE varies significantly enough to cause composite failure because of material separation during thermal cycling. Also, binding during shrink-fit operations could occur due to expansion in the "c" direction. Further analysis and experimentation will have to be undertaken to confirm and resolve these problems

The problem of carbonization of barrel steel during thermal cycling was investigated Nucleation of carbon atoms along the steel grain boundaries could initiate microscopic cracking due to material hardening, but the feasibility of composite failure due to carburizing was determined minimal

<u>Forming Processes</u>

The primary consideration in the forming process is that of the structural integrity of the composite gun tube Basic design considerations used as guidelines for this investigation are listed below:

1. Liner and sleeve assemblies must be the primary load-carrying composite members.

2. Feasibility must be determined for application of precompressive loading at the interface to offset tensile stresses generated by pressure and thermal stressing

3. Significant design changes to the overall weapons system must be kept to a minimum

4. Bore liner material must withstand the higher bore temperatures engendered by application of the thermal barrier.

Three principal fabrication processes have been investigated. These are as follows:

1. Shrink-fit assembly (one- or two-piece approach).

2. Swaging of outer sleeve over inner liner and interface material.

3. Hot coextrusion of entire three-piece assembly.

All these processes require three major components, an inner liner, a thermal interface resistance material, and an outer retaining sleeve. Each of these processes will be discussed in the following sections.

Shrink Fit

Current manufacturing procedures limit the shrinkage length to approximately 10 inches. By an increase in the assembly rate, an increase in the temperature difference between sections, and an increase in the clearance tolerances (a reduction in final interference between sections), longer length fits can be achieved. By controlled procedures, sections have been assembled in excess of 30 inches. Initial design work on an M60 gun barrel indicates that a one-piece shrink-fit can be accomplished.

The primary advantages of a shrink-fit assembly are listed below:

1. Solid interface sections may be employed, either by flame spraying the interface material on the liner, by use of free-standing ceramic cylinders, or by use of ceramic tapes or fabrics.

2. A precompressive load may be applied (dependent upon the amount of interference desired) to the ceramic interface, thus the initial stress characteristics are enhanced.

With a solid interface section configuration, the bonding mechanism between liner and interface material, and likewise between interface material and outer sleeve, should be considered. Bonding may be established through mechanical means such as roughened surfaces, cements, or flame-spray coats.

Initial calculations performed for an M60 gun barrel show that a precompressive load of 59,000 psi can be developed for a 1.5-mil interference. An expansion of 2.5-mils can be achieved with a temperature difference of 1000°F. Hence, by an increase in assembly rates, a longer shrink-fit apparently can be achieved.

Swaging

Swaging has a direct application for the forming of a composite material barrel blank. The process is relatively inexpensive when compared with other processes. Major problems are generated in the swaging of brittle materials. Rotary swaging will cause, as a function of radial angle and axial speed of the workpiece, an uneven reduction in material cross-section. The cyclical nature (a fluctuating angular radial force) of the swaging process and the low impact-resistance of ceramic materials will cause pulverization of the ceramic interface during assembly; this results in the ejection of the ceramic material from the assembly. Also, interface material will be unevenly distributed around the circumference of the assembly. Even though solutions to the many problems associated with the swaging process have not yet been determined, this process is believed to have excellent potential in view of the low process cost involved.

Hot Extrusion

Under normal practice, when two or more materials are extruded together, they become metallurgically bonded at the interface. In the case of ceramics and metals, this action does not occur. An end configuration comprises an inner liner, a densely compacted oxide powder, and an outer sleeve. Because of the differences in hot working temperatures (Cr-Mo-V steel from 1900°F to 2100°F and ZrO_2 approximately 4800°F), plastic deformation of the ceramic material is impossible without exceeding its ultimate shear strength. The resulting interface transmits hoop stresses and thermal stresses to the strength-bearing members. However, axial shear-stresses due to projectile frictional forces can cause assembly failure.

A number of approaches for the solution to the problem of axial shear failures are as follows:

1. Electron beam-welding of retaining rings over the muzzle and breech ends of the gun barrel. This approach is applicable to all processes under discussion.

2. Another approach, applicable to hot extrusion, would involve the use of liner supports. These supports would be

attached periodically along the length of the liner (similar to cooling fins). Ceramic material would be used to make up the remainder of the annulus. The liner, liner support, ceramic, and sleeve section would then be extruded. The resulting configuration would consist of a liner support, metallurgically bonded to both the liner and the sleeve assembly, with the interface material distributed between the liner support as a high density powder.

3. The interface material can be alloyed with free metallic atoms, copper for example. The percentage of alloying can be varied from 10 to 20 per cent of the interface material. During extrusion, the alloyed material will flow and form metallurgical bonds with the liner and the sleeve assemblies. The resultant configuration would consist of a solid interface material that could withstand axial shear.

FUTURE EFFORTS

Presently, two gun barrels are being evaluated for fabrication of a full-length thermal resistance interface. The two gun barrels are an M60 7.62mm and a MK11 Mod. 5, 20mm. Preliminary design of an M60 gun tube with a shrink-fit assembly (30 mil coating of ZrO_2, high-density flame spray) is nearing completion. A major redesign of the breech section is necessarily unavoidable to inclose a full-length interface barrel. An extensive test program will be initiated to measure temperature profiles and erosion wear as a consequence of high bore-temperatures.

A coextrusion process is under investigation for placing a 30- to 35-mil ZrO_2 interface into a MK11 Mod. 5 gun barrel. This investigation includes selection of the liner material and the outer sleeve material consistent with the coextrusion-process and the operational temperatures. Three complete MK11 gun barrels are contemplated for fabrication and testing.

SUMMARY AND CONCLUSIONS

A second live-firing experiment was completed using an M60 gun barrel with a ZrO_2 thermal interface as the test vehicle. The test section for this experiment was located near the muzzle end. Good correlation between theory and experimentation was obtained. A significant number of rounds were fired with no apparent deterioration of the modified section. Experimental results further substantiate the temperature reduction for the outer sleeve of the modified section. The significance of this temperature reduction becomes more apparent when axial conduction into the test section from the unmodified portions of the gun barrel are taken into account.

Design criteria have been established for two full-length thermal interface gun barrels. The 7.62mm, M60 gun barrel will consist of a shrink-fitted outer sleeve over a coated liner. The 20mm design, however, will be based on a coextruded composite gun barrel with ZrO_2 positioned between a high-temperature liner material and an outer sleeve of Cr-Mo-V steel. Future efforts by the Research Directorate, Weapons Laboratory at Rock Island will involve the fabrication and testing of these full-length modified gun barrels.

APPENDIX A

Digital Computer Program for Calculating Propellant Gas Convection Coefficient and Temperatures

```
C        PROGRAM TO DETERMINE VALUES FOR HG & TG      2/18/71
      DIMENSION BB(20), CC(420), DD(420),          HBAR(5),TW(5),DTWDT(5)
     1, TB(5), TO(5), TT1(20), CP1(20), YI(30)
      COMMON /BLK2/ X(30), Y1(30), Y2(30), DTDT(30), YY(30)
C
C        TW - AVERAGE  WALL TEMPERATURE
C        RHO - DENSITY
C        CP - SPECIFIC HEAT
C        HBAR - EFFECTIVE CONVECTION COEFFICIENT
C        HBAR =XK1 * TW**2 +XK2 * TW +XK3
C        DR - DELTA R
C        TA - AMBIENT TEMPERATURE
C        THETA - TIME
C        RI IS BORE RADIUS
C        RO IS OUTSIDE RADIUS
C       RATIO IS FROM 1 THRU RO/RI
C        IKKMAX REPRESENTS NUMBER OF -TIME VS TEMP- DATA CHANGES
      IKKMAX = 1
      DO  111 IKK = 1,IKKMAX
C        N REPRESENTS NUMBER OF ORDERED PAIRS.
      READ  1, N, (X(I), Y1(I), I =1,N)
    1 FORMAT(I5/(2F10.0))
C        M IS THE NUMBER OF CONSTANTS NEEDED FOR DEGREE OF POLYN. DESIRED.
      M = 3
C        NC IS THE NUMBER OF PASSES THROUGH LEAST SQUARES SUBROUTINE, AT THIS
C          POINT IS USED ONLY TO MATCH TIME VS. TEMPERATURE.
      NC = 1
      CALL LSTSQ(M,N,NC)
      DO  3 IJ = 1, N
    3 YI(IJ) = YY(IJ)
      READ 5,IRATIO,RI, RO, RHO, CP, XK1, XK2, DR, TA, XK3
    5 FORMAT(I5/(8F10.0))
      DR = RO - RI
C       IRATIO IS THE NUMBER OF RATIO TESTS PER EACH IKK
      DO  110 IJI = 1, IRATIO
      READ 8, RATIO
    8 FORMAT(F10.0)
      RO = RATIO * RI
C
      II = 0
C        N IS THE NUMBER OF DATA SETS.
      NN = N - 1
C        NN IN NEXT CARD MUST BE CORRECT NUMBER OF DATA SETS READ IN - ONE * *
      DO 100  IJ = 1,NN
      TO(1) = YI(IJ)
      DTWDT(1) = DTDT(IJ) * 3600.0
      TO(2) = YI(IJ + 1)
```

```
      DTWDT(2) = DTDT(IJ + 1) * 3600.0
C
      PRINT 20, RATIO,    TO(1),TO(2),DTWDT(1), DTWDT(2),RHO, CP,XK1,
     1 XK2, DR, TA, XK3, RI, RO
   20 FORMAT(10H RO / RI =,F12.4, 10X,                8H TO(1) =,F12.4,
     1 10X, 8H TO(2) =,F12.4/7H DT(1)=,F12.4, 10X, 6HDT(2)=,F12.4, 10X,
     2 6H RHO =,F12.4, 10X, 5H CP =,F12.4/ 5H K1 =,E12.4,5X,5H K2 =,
     3 E12.4, 5X, 5H DR =, E12.4,5X,5H TA =,F8.1/15X, 6H XK3 =, E12.6,
     4  10X,14H BORE RADIUS =,E12.6, 10X, 17H OUTSIDE RADIUS =, E12.6//)
      DO 30 I = 1, 2
      HBAR(I) = XK1 * TO(I) ** 2 + XK2 * TO(I) + XK3
      PRINT 25,I,HBAR(I)
   25 FORMAT( 8H  HBAR( ,I2,5H ) = ,E12.5)
   30 CONTINUE
      AB = 2. * RI
      AO = 2. * RO
      AM = RI + RO
      TM1 = AM * (DTWDT(1) - DTWDT(2)) * RHO * CP * DR
      PRINT  35, AB, AO, AM, TM1
   35 FORMAT(/6H AB = ,E12.4,6H AO = ,E12.4,5X,6H AM = ,E12.4,5X,
     1  14H FIRST TERM = ,E12.4/)
C
      HG = TM1 / ((TO(2) - TO(1)) * AB)
      TGAV = 0.0
      DO  50 I = 1,2
      TT = TO(I)
      TG = TO(I) + (RHO*CP*DR* AM * DTWDT(I)) / HG / AB
      TGAV = TGAV + TG
      PRINT 40, HG, TG
   40 FORMAT(5H HG =,E12.4, 10X, 5H TG =,E12.4)
   50 CONTINUE
      TGAV = TGAV / 2.
      DTO = TO(2) - TO(1)
      TAVG = TO(1) + DTO / 2.
      PRINT 55, DTO, TAVG, TGAV
   55 FORMAT(18H TEMP DIFFERENCE =, E12.5, 15X, 23H AVERAGE OUTSIDE TEMP
     1 =, E12.4, 10X, 14H TG(AVERAGE) =, E12.4/)
C
C        THE SECOND QUANTITY IN THE FOLLOWING STATEMENT REPRESENTS THE
C           TOLERABLE DIFFERENCE BETWEEN CONSECUTIVE TEMPERATURES.
C       FOLLOWING NUMBER (300.0) MAY HAVE TO BE LOWERED
      IF(DTO .GT. 300.0) GO TO 100
C        II REPRESENTS THE NUMBER OF ORDERED PAIRS.
      II = II + 1
      ID = II
      X(II) = TAVG
      Y1(II) = HG
      Y2(II) = TGAV
      IM = II
   70 IM = IM - 1
      IF(X(ID) .GE. X(IM)) GO TO 80
      XD = X(ID)
      Y1D = Y1(ID)
      Y2D = Y2(ID)
      X(ID) = X(IM)
      Y1(ID) = Y1(IM)
      Y2(ID) = Y2(IM)
      X(IM) = XD
      Y1(IM) = Y1D
      Y2(IM) = Y2D
      ID = ID -1
```

```
      GO TO 70
   80 CONTINUE
C        NOW ORDERED - AND II VALUE IS THE NUMBER OF ORDERED PAIRS    ----
C
  100 CONTINUE
C
      PRINT 105, (X(I), Y1(I), Y2(I), I = 1, II)
  105 FORMAT(10X, E12.5, 10X, F12.5, 10X, E12.5)
      M = 4
      NC = 2
      CALL LSTSQ(M,II,NC)
  110 CONTINUE
  111 CONTINUE
      CALL EXIT
      END

      SUBROUTINE LSTSQ(M,N,NC)
      DIMENSION B(20),C(420),D(420)
      COMMON /BLK2/ X(30), Y1(30), Y2(30), DTDT(30), YY(30)
C         THIS SUBROUTINE IS GOOD FOR SECOND OR THIRD DEGREE POLYNOMIALS, ONLY.
C        M = NUMBER OF CONSTANTS NEEDED FOR DEGREE OF POLYNOMIAL DESIRED.
C           KEEP THE POLYNOMIAL AT DEGREE TWO TO AVOID POINTS OF INFLECTION.
C        N = NUMBER OF ORDERED PAIRS READ IN.
      DO 1 I=1,N
    1 YY(I) = Y1(I)
C         NC = 1 THE FIRST TIME THROUGH (MATCHES TIME VS TEMP).
C           NC = 2 THE SECOND, AND LAST, TIME THROUGH(MATCHES TIME VS HG AND TIME
C              VS TG(AVE) ).
      DO 400    IJK = 1,NC
      N1=(M+1)*M
      DO 2 I=1,N1
    2 D(I)=0.
      K=1
    3 XX = X(K)
      Y = YY(K)
      B(1)=1.
      DO 4 I=2,M
      IEXP=I-1
    4 B(I)=XX **IEXP
      II=0
      I=1
      J=1
      JJ=0
    5 ISUB1=II+I+JJ
      ISUB2=I+JJ
      C(ISUB1)=B(J)*B(ISUB2)
      D(ISUB1)=D(ISUB1)+C(ISUB1)
      IF(I+JJ .GE. M) GO TO 6
      I=I+1
      GO TO 5
    6 I=I+1
      ISUB1=II+I+JJ
      C(ISUB1)=B(J)*Y
      D(ISUB1)=D(ISUB1)+C(ISUB1)
      IF(J .GE. M) GO TO 7
      II=II+M+1
      J=J+1
      I=1
      GO TO 5
    7 K=K+1
```

```
      IF(K .LE. N) GO TO 3
      JJ=M+1
      J=1
      I=2
      K=0
      NIN=1
    9 IJOB1=JJ+J
      IJOB2=I+K
      D(IJOB1)=D(IJOB2)
      IF(J .GE. NIN) GO TO 11
      K=K+M+1
      J=J+1
      GO TO 9
   11 NIN=NIN+1
      K=0
      I=I+1
      J=1
      JJ=JJ+M+1
      IF(JJ .LE. (M-1)*(M+1)) GO TO 9
C     NORMAL EQUATIONS IN D(I) COMPLETED TO HERE
      IN=1
      IOUT=M+1
      DO 40 LP=1,M
      M8=M+1
      DO 20 I=1,M8
   20 C(I)=D(I)
      IF(C(1) .EQ. 0.0) GO TO 800
      J=M+2
      M3=(M-2)*M8
      K=0
   25 DO 30 II=1,M
      IIP=II+K
      IIQ=J+II
   30 D(IIP)=D(IIQ)-D(J)*C(II+1)/C(1)
      D(IIP+1)=-D(J)/C(1)
      J=J+M8
      K=K+M8
      IF(K .LE. M3) GO TO 25
      DO 35 II=1,M
      IIR=II+K
   35 D(IIR)=C(II+1)/C(1)
      D(IIR+1)=1./C(1)
   40 CONTINUE
      JX=0
      DO 50 I=1,N1,M8
      JX=JX+1
      B(JX)=D(I)
   50 CONTINUE
      PRINT 53
   53 FORMAT(//53H COEFFICIENTS OF FITTED CURVE BEGINNING WITH CONSTANT
     1//)
      PRINT 54, (D(I),I=1,N1 ,M8)
   54 FORMAT(4D20.8)
      IF(M .EQ. 4) GO TO 68
      NBC=1+M8
      NAC=NBC+M8
      BC=D(NBC)
      AC=D(NAC)
      GO TO 76
   68 NCC = 1 + M8
      NBC =NCC + M8
```

```
      NAC = NBC + M8
      CC = D(NCC)
      BC=D(NBC)
      AC=D(NAC)
   76 PRINT 77
   77 FORMAT(//14X1HX19X1HY17X8HFITTED Y15X5HSLOPE)
      IF(M .NE. 3) GO TO 79
      BAA = - BC / 2. / AC
      PRINT 78, BAA
   78 FORMAT(/25X, 29H VERTEX OF PARABOLA IS AT X =, E12.4/)
      GO TO 84
   79 XINFLP = -(2. * BC) / 3. / (3. * AC)
      PRINT 80, XINFLP
   80 FORMAT(/10X, 27H*** INFLECTION POINT AT X =, E12.4, 4H ***/)
      DISC = (2. *BC) ** 2 - 4. * (3. * AC) * CC
      IF(DISC .LT. 0.0) GO TO 82
      R1 = (-2. * BC + SQRT(DISC)) / 2. / (3. * AC)
      R2 = (-2. * BC - SQRT(DISC)) / 2. / (3. * AC)
      PRINT 81, R1, R2
   81 FORMAT(/28H THE REL MAX AND/OR MIN ARE , 5X, E12.4, 10X, E12.4/)
      GO TO 84
   82 PRINT 83
   83 FORMAT(/57H THE THIRD DEGREE POLY HAS NO REL MAX NOR REL MIN VALUE
     1S /)
      IF(NC .NE. 2) GO TO 89
   84 IF(IJK .EQ. 2) GO TO 87
      PRINT 86
   86 FORMAT(/15X, 34H *****  TEMP(OUTSIDE) VS HG   *****/)
      GO TO 89
   87 PRINT 88
   88 FORMAT(/15X, 34H *****  TEMP(OUTSIDE) VS TG   *****/)
   89 DO 121 LLL=1,N
      XX = X(LLL)
      Y = YY(LLL)
      YF=0.0
      DO 94 I=1,M
      IEXP=I-1
      IXI=XX
      IF(IXI .NE. 0) GO TO 93
      IF(IEXP.NE. 0) GO TO 92
      YF=YF+B(I)
      GO TO 94
   92 YF=YF
      GO TO 94
   93 YF=YF+B(I) * XX **IEXP
   94 CONTINUE
      IF(M .EQ. 4) GO TO 96
      DT=2.*AC*XX + BC
      GO TO 98
C  96 DT = 3. * B(4) * XX** 2 + 2. * B(3) *XX + B(2)
   96 DT = 3. * AC    * XX** 2 + 2. * BC    *XX + CC
   98 IF(NC .EQ. 2) GO TO 99
      IF(NC .EQ. 1) YY(LLL) = YF
      DTDT(LLL) = DT
   99 PRINT 120,XX, Y, YF, DT
  120 FORMAT(//4F20.6)
  121 CONTINUE
      IF(NC .EQ. 1) GO TO 800
      IF(IJK .EQ. 2) GO TO 400
      DO 131 I = 1,N
  131 YY(I) = Y2(I)
```

```
400 CONTINUE
800 RETURN
    END
```

APPENDIX B

Gun Barrel Heat Transfer Program
Utilizing Crank-Nicolson Algorithm

```
C  ONE-DIMENSIONAL TRANSIENT HEAT CONDUCTION PROGRAM (HT-2A)
C  THIS PROGRAM IS A GENERAL PROGRAM FOR THE SOLUTION OF CONDUCTION
C  PROBLEMS WITH TEN OR LESS REGIONS INCLUDING INTERFACIAL RESISTANCES
C  BETWEEN REGIONS
      DIMENSION IDFELD(9)                                                C
      DATA IDFELD /'    ','STEV','E BO','STWI','CK  ','AMSW','E-RE','T-E  C
     1A','    '/                                                         C
      WRITE(14) IDFELD                                                   C
      DIMENSION XLAB(5),YLAB(5),GLAB(5),DATLAB(5)                        C
      DIMENSION XBS(5),YBS(5),GBS(5),DBS(5)                              C
      DIMENSION LABL1(20),LABL2(20),LABL3(20),LABL4(20),LABL5(20),LABL6( C
     120),LABL7(20),LABL8(20)                                            C
      DIMENSION LABL9(20),LABL10(20),LABL11(20),LABL12(20),LABL13(20),LA C
     1BL14(20),LABL15(20),LABL16(20),LABL17(20),LABL18(20),LABL19(20),LA C
     2BL20(20),LABL21(20)                                                C
      DIMENSION LABL22(20),LABL23(20),LABL24(20),LABL25(20),LABL26(20),L C
     1ABL27(20),LABL28(20),LABL29(20),LABL30(20),LABL31(20)              C
      READ 500,XLAB,YLAB,GLAB,DATLAB                                     C
      READ 500,LABL1,LABL2,LABL3,LABL4,LABL5,LABL6,LABL7,LABL8           C
      READ 500,LABL9,LABL10,LABL11,LABL12,LABL13,LABL14,LABL15,LABL16,LA C
     1BL17,LABL18,LABL19,LABL20,LABL21                                   C
      READ 500,XBS,YBS,GBS,DBS                                           C
      READ 500,LABL22,LABL23,LABL24,LABL25,LABL26,LABL27,LABL28,LABL29,L C
     1ABL30,LABL31                                                       C
  500 FORMAT(20A4)                                                       C
      DIMENSION TRAD(20), RADIST(20)
      DIMENSION TBR(100),TOS(100),TME(100)                               C
C          END PLOT DIMENSION                                            C
      DIMENSION                          TT(150),    RHOP(20),
     1 HG(20),           TG(20),          TT1(20), CP1(20)
C
C**DEFINITION OF LABELED COMMON -- BLK1,BLK2, AND BLK3
      COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
      COMMON /BLK2/ RADII(11),NODES(10),XK7(20),BETA(10),CP(20),RHO(20),
     2EMISS,RHOZ,CPZ,XKRZ,BDYR(11),RI(150),RII(150),DR(10),A(9),ITB(11)
C
C**INITIALIZATION OF VARIABLES NOT LOCATED IN LABELED COMMON
      DATA   KRUN,    TNUM,TDENOM,DZ,DTIMEX,DDTX,IX,NBODY/  1,
     2              .0, 1., 1., .005, .25, 3, 2/
C
C**READ CHARACTERISTICS OF PROBLEM -- RAW INPUT DATA
C
C**DEFINITION OF NAM AND NAM1
      NAMELIST /NAM/ T,KRUN,TNUM,TDENOM, NODES, XKZ,BETA,CP,RHO,BDYR,
     2EMISS,DZ,    DTIMEX,DDTX,IX,NBODY,CPZ,RHOZ,XKRZ,RADII,A,ITB,NRD,NSC
     4/NAM1/DTIMEX,DDTX,DZ,II,NBODY,IX,XKRZ,RHOZ,CPZ,EMISS,TNUM,TDENOM,
     5 NODES,    A,ITB,NRD,NSC
C        N2N=2  CHECKS NO. OF ROUNDS AS A MULTIPLE OF 2.
```

```
      N2N=2
      KKR= 0
C**********NCPLOT = 0, -1, OR 1 ********************************************
C*********** NCPLOT = -1 WHEN NO PLOT IS DESIRED ****************************
C*********** NCPLOT = 0 WHEN BOTH RADIAL AND BCS PLOTS ARE DESIRED***********
C*********** NCPLOT = 1 WHEN ONLY ONE OF THE TWO TYPES OF PLOTS IS DESIRED****
C**********NBRPLT = 0, OR 1 ***********************************************
C*********** NBRPLT = 0 WHEN THE RADIAL OR BOTH THE PLOTS ARE DESIRED*********
C*********** NBRPLT = 1 WHEN ONLY THE BCS PLOT IS DESIRED********************
C***********WHEN NCPLOT = 0, NBRPLT MUST ALSO = 0. ****************************
      NCPLOT =-1
      NBRPLT = 0
      IF ( NCPLOT .EQ. -1 ) GO TO 2
      IF ( NBRPLT . EQ . 1 ) GO TO 480
      KRAD = 0
      IF ( NCPLOT .EQ. 0 ) GO TO 480
      GO TO 2
  480 KBRSK = 1
      TBR(KBRSK) = 70.0
      TOS(KBRSK) = 70.0
      THE(KBRSK) = 0.0
    2 READ(5,NAM)
C
C        FOLLOWING CARDS ARE REQUIRED IF DESIRE TO RETAIN TIME PER BURST,
C          BUT A LOCATION CHANGE REQUIRES VARYING BARREL THICKNESS.
C        DZOLD IS ORIGINAL DZ VALUE IN FEET.
      DZOLD = .02756
C        DZNEW IS PRESENT VALUE OF DZ.
      DZNEW = DZ
      DTIMEX = DZOLD ** 2. * DTIMEX / DZNEW ** 2
C
C
      IOUT = 0
      DO 3 I = 1,NBODY
    3 IOUT = IOUT + NODES(I)
      IOUT = IOUT + 1
      TOUTS = T(IOUT)
      CALL TGHG(TOUTS,TOTS,AVGHG)
      T(1) = TOTS
      BOYR(1) = XKR2 / AVGHG
C
C        IF NCK STAYS ZERO THEN THERE IS AN EVEN NO. OF ROUNDS PER BURST.
      NCK=0
      IXX= 50/NRD
      IF(IXX.EQ. 0) IXX=1
      IF(MOD(NRD,N2N) .EQ. 0) GO TO 4
      NCK= 1
      DTIMEX= DTIMEX/2.
C        IXX REPRESENTS THE BURST TO BE PRINTED (EVERY IXX BURST).
C        NRD REPRESENTS THE NO. OF ROUNDS PER BURST.
C        NSC REPRESENTS THE NO. OF SECONDS OF COOLING.
    4 PRINT 202,NRD,NSC
  202 FORMAT(1H1,15X,I5,10H ROUND BURSTS AND ,I5,16H SECONDS COOLING/)
      NIB=NRD/2
C        NIB IS NUMBER OF PASSES PER BURST
      IF(NCK .EQ. 1)  NIB = NRD
C     NIC=NIB*NSC*10/3       (IF A MULTIPLE OF 3)
      NIC = NIB * NSC * 10 / 2
C        NIC IS NUMBER OF PASSES PER BURST PLUS NUMBER THRU COOLING
      NNIC = (NIC - NIB) / 2 + NIB
      NAM=0
```

```
C
C**CALCULATE DIMENSIONLESS LUMPED PARAMETERS, HX(I) AND C(I)
C
      CALL LUMP (II,NBODY,DZ,TT1,CP1)
C
C
C**WRITE PROBLEM PARAMETERS
      WRITE(6,NAM1)
      WRITE(6,5)
5     FORMAT(7HOREGION,3X5HIBODY,3X 9HRADII(FT),5X6HDR(FT),5X8HBDYR(FT),
     26X2HCP,8X3HRHO,8X2HKZ,6X4HBETA )
      WRITE(6,7) (J,IBODY(J,1),IBODY(J,2),RADII(J),DR(J),BDYR(J),CP(J),
     2RHO(J),XKZ(J), BETA(J), J=1,NBODY)
7     FORMAT(I3,I8,I4,3E12.3,  F10.3,2F10.1,F11.6)
      I = NBODY + 1
      WRITE(6, 9)I,RADII(I),BDYR(I)
9     FORMAT(I3,12X,E12.3,12X,E12.3//)
      WRITE(6,11)
11    FORMAT(3X1HI,7X5H H(I), 12X4HC(I), 12X4HT(I),  7X6HRADIUS )
      WRITE(6,13)(I, H(I),C(I),T(I),RI(I),   I=1,II)
13    FORMAT(I4,2E16.4,F13.2,F13.5)
      JI = II-1
      DO 90 I=2,JI
      RADIST(I-1) = RI(I)
   90 CONTINUE
      JJJ = I-1
C
C**CALCULATE OR INITIALIZE VARIOUS QUANTITIES --- SAVE T(I) AND DTIMEX
      TSEC = DZ**2*RHOZ*CPZ*3600./XKRZ
      IIM1 = II - 1
      IIM2 = II - 2
      IIP1 = II + 1
      DO 15 I=1,IIP1
15    TT(I) = T(I)
      ATIME = DTIMEX
      DDDTX=DDTX
      N=0
      NMN = 0
      TAUT = .0
       CALL TAVE(II,IIP1)
C
      SQIN = 0.0
      SQSTR = 0.0
      SQUT = 0.0
      NT = 0
      DO  17 J = 1,NBODY
      NT1 = NT + 1
      NT = NODES(J) + NT
      DO  17 I = NT1,NT
   17 RHOP(I) = RHO(J)
C
C
C**START OF SOLUTION OF PROBLEM
C
   18 CONTINUE
      TOUTS = T(IOUT)                                                  LEECH
      CALL TGHG(TOUTS,TOTS,AVGHG)
      T(1) = TOTS
      BDYR(1) = XKRZ / AVGHG
      CALL LUMP (II,NBODY,DZ,TT1,CP1)
C
```

```
C  POINT OF MAJOR LOOP ENTRY -- SN25(NO NEW DTIMEX), SN24(NEW DTIMEX)
      IF(IRET .EQ. 2) GO TO   25
      DO 19 I=2,IIM1
19    CX(I) = C(I)/DTIMEX*2.
   25 NNMM = NMN
      CALL CHANGE(NBODY,TSEC,TAUT,II,IX,N,NMN,NIB,NIC)
      NMN = NNMM
      CALL SOLVE (IIM1,IIM2,II,NBODY,BETA,TAUT)
C
      DETM = DTIMEX * TSEC / 3600.0
      QSTR = 0.0
      DO  27 I = 1, NT
      QSTR = (RI(I + 1) - RI(I))* RHOP(I) * CP(I) *  6.2832 * RI(I) * (T
     1(I) - TT( I)) / DETM + QSTR
   27 CONTINUE
      QIN = HX(1)*XKRZ*6.2832*(T(1) - T(2))
      QOUT = HX(IIM1)*XKRZ*6.2832*(T(IIM1) - T(II))
      SQIN = SQIN + QIN * DETM
      SQSTR = SQSTR + QSTR * DETM
      SQUT = SQUT + QOUT * DETM
      SUM = SQSTR + SQUT
      ENBL = (SQIN - SUM) / SQIN * 100.0
C
      DO 29 I=1,IIP1
   29 TT(I) = T(I)
      N = N + 1
      NMN = NMN + 1
      TAUT = TAUT +DTIMEX
C
C**IF N/IX IS AN INTEGER CALCULATE VARIOUS QUANTITIES AND STORE ITEMS
       CALL TAVE(II,IIP1)
C
C**END OF TIME STEP
      IF(NMN .NE. NIB)  GO TO  31
      DTIMEX = DTIMEX * 2.
      WRITE(6,203) DTIMEX,NIB
  203 FORMAT( /21H NMN=NIB AND DTIMEX =,E12.5,10X,6H NIB =,I5)
      GO TO 33
   31 IF(NMN .NE. NIC)  GO TO 33
      DTIMEX = DTIMEX / 2.
      WRITE(6,204) DTIMEX,NIC
  204 FORMAT( /21H NMN=NIC AND DTIMEX =,E12.5,10X,6H NIC =,I5)
   33 IF(NCK .NE. 1)  GO TO 35
      IRET = 1
      GO TO 37
   35 IRET = 2
   37 IF(NMN .EQ. NIC) GO TO 41
      IF(MOD(NMN, 25) .NE. 0) GO TO  18
      GO TO 42
   41 NMN = 0
      NXM=NXM+1
   42 IF(MOD(NXM,IXX) .NE. 0) GO TO  18
      CALL RESULT(TAUT,IIM1,II,TNUM,TDENOM,DZ,NBODY,QSTR,DETM,SQSTR,ENBL
     2,IIP1,SQIN,SQUT,TIME)
      IF ( NCPLOT .EQ. -1 ) GO TO 331
      IF ( NCPLOT .EQ. 1 .AND. NBRPLT .EQ. 1 ) GO TO 321
      KRAD = KRAD+1
      TME(KRAD) = TIME
      DO 311 I=2,15
      TRAD(I-1) = T(I)
  311 CONTINUE
```

```
      CALL GRAPH(JJJ,RADIST,TRAD,11,1,10.5,10.5,0,0,0,0,XLAB,YLAB,GLAB,D
     1ATLAB)
       ALL LETTER(2.0,9.8,0.2,LABL1,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(1.0,1.6,0.1,LABL2,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(1.0,1.4,0.1,LABL8,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(1.0,1.2,0.1,LABL4,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(1.0,1.0,0.1,LABL3,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(1.0,0.8,0.1,LABL6,0,80,0,0,0,0,0,0,0,0)
      GO TO (700,710,720,730,740,750,760,770),KRAD
  700 CALL LETTER(1.0,0.6,0.1,LABL5,0,80,0,0,0,0,0,0,0,0)
      GO TO 888
  710 CALL LETTER(1.0,0.6,0.1,LABL9,0,80,0,0,0,0,0,0,0,0)
      GO TO 888
  720 CALL LETTER(1.0,0.6,0.1,LABL10,0,80,0,0,0,0,0,0,0,0)
      GO TO 888
  730 CALL LETTER(1.0,0.6,0.1,LABL11,0,80,0,0,0,0,0,0,0,0)
      GO TO 888
  740 CALL LETTER(1.0,0.6,0.1,LABL12,0,80,0,0,0,0,0,0,0,0)
      GO TO 888
  750 CALL LETTER(1.0,0.6,0.1,LABL13,0,80,0,0,0,0,0,0,0,0)
      GO TO 888
  760 CALL LETTER(1.0,0.6,0.1,LABL14,0,80,0,0,0,0,0,0,0,0)
      GO TO 888
  770 CALL LETTER(1.0,0.6,0.1,LABL15,0,80,0,0,0,0,0,0,0,0)
  888 CALL LETTER(1.0,0.2,0.1,LABL7,0,80,0,0,0,0,0,0,0,0)
      IF ( NCPLOT .EQ. 0 ) GO TO 321
      GO TO 331
  321 KBRSK = KBRSK+1
      TBR(KBRSK) = T(2)
      TOS(KBRSK) = T(IOUT)
      TME(KBRSK) = TIME
C        NXM INDICATES WHICH BURST HAS BEEN FIRED.
  331 IF(NXM .GE. 1)  GO TO 45
C        ABOVE IF STATEMENT INDICATES NUMBER OF BURSTS TO BE FIRED.
      GO TO 18
C                                                                       01200
C**RESET INITIAL CONDITION AND TIME INCREMENT -- READ NEXT CASE -- SN26 01210
   45 KKR = KKR + 1
      IF ( NCPLOT .EQ. -1 ) GO TO 365
      IF ( NCPLOT .EQ . 0 .AND. NBRPLT .EQ. 0 ) GO TO 360
      IF ( NBRPLT .EQ. 0 ) GO TO 365
  360 CALL GRAPH(KBRSK,TME,TBR,11,1,10.5,10.5,0,0,0,0,XBS,YBS,GBS,DBS)
      CALL GRAPH(KBRSK,TME,TOS,11,1,0,0,0,0,0,0,0,0)
      CALL LETTER(2.0,9.5,0.2,LABL22,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(2.0,9.1,0.2,LABL23,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(2.5,2.3,0.1,LABL24,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(2.5,2.1,0.1,LABL25,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(2.5,1.9,0.1,LABL26,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(2.5,1.7,0.1,LABL27,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(2.5,1.5,0.1,LABL28,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(2.5,1.3,0.1,LABL29,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(2.5,1.1,0.1,LABL30,0,80,0,0,0,0,0,0,0,0)
      CALL LETTER(2.5,0.9,0.1,LABL31,0,80,0,0,0,0,0,0,0,0)
  365 IF(KRUN .GE. KKR) GO TO 370
      DTIMEX = ATIME
      DO 47 I=1,IIP1
   47 T(I) = TT(I)
      GO TO 2
  370 CALL EXIT
      END                                                               01260
      SUBROUTINE LUMP(II,NBODY,DZ,TT1,CP1)
```

```
      DIMENSION                    TT(150),     RHOP(20),
     1 HG(20),          TG(20),            TT1(10), CP1(10)
C
      COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
      COMMON /BLK2/ RADII(11),NODES(10),XKZ(20),BETA(10),CP(20),RHO(20),
     2EMISS,RHOZ,CPZ,XKRZ,BDYR(11),RI(150),RII(150),DR(10)
C
C**THIS SUBROUTINE CALCULATES THE DIMENSIONLESS LUMPED PARAMETERS
      AZ=RHOZ*CPZ*DZ**2
      CI = .0
      C(1) = .0
      IF(BDYR(1).EQ..0) GO TO 3
      HX(1) = RADII(1)/BDYR(1)
      H(1) = HX(1)
      IBODY(1,1) = 2
      GO TO 5
3     IBODY(1,1) = 1
5     RI(1) = RADII(1)
C
C**BEGINNING OF LOOP TO CALCULATE C(I) AND H(I) FOR NBODY REGIONS(J)
      DO 9 J=1,NBODY
      DRR = RADII(J+1) - RADII(J)
      DR(J) = DRR/FLOAT(NODES(J)-1)
      IBODY(J,2) = IBODY(J,1) + NODES(J) - 1
      IB = IBODY(J,1)
      IE = IBODY(J,2) - 1
      RI(IB) = RADII(J)
C
C**CALCULATION OF C(I) AND H(I) FOR REGION J
      DO 1 I=IB,IE
C
C**USE FOLLOWING IF WANT VARIABLE CP.
C     IXI = 1
C     TEMP1 = T(I)
C     CALL LINEAR(TEMP1,TT1,CP1,CPJ,IXI)
C     CP(I) = CPJ
C
      IF(J .NE. 2) CP(I) = .11
      IF(J .EQ. 2) CP(I) = .18
      AJ = RHO(J)*CP(I)*DR(J)/AZ
      C(IB) = AJ*(RI(IB) + DR(J)/4.)/2.+ CI
      CALL XKKS(I,XKZJ)
      XKZ(I) = XKZJ
      IF(J .EQ. 2) XKZ(I)=1.0
      XKDR = XKRZ * DR(J)
      BJ = XKZ(I)/(XKRZ*DR(J))
C
      H(I) = BJ*(RI(I)+DR(J)/2.)
      RI(I+1) = RI(I) + DR(J)
1     C(I+1) = AJ*RI(I+1)
      C(IE+1) = AJ*(RI(IE+1)-DR(J)/4.)/2.
C
C**CECK TO SEE IF INTERFACIAL RESISTANCE IS ZERO AND PROCEED ACCORDINGLY
      IF(BDYR(J+1).EQ..0) GO TO 2
      CI = .0
      IBODY(J+1,1) = IBODY(J,2) + 1
      HX(IE+1)= RI(IE+1)/BDYR(J+1)
      H(IE +1) = HX(IE+1)
      GO TO 9
2     CI = C(IE+1)
      IBODY(J+1,1) = IBODY(J,2)
```

```
9       CONTINUE
        IF(BDYR(NBODY+1).NE..0) GO TO 11
        II = IE + 1
        GO TO 13
11      II = IE +2
        C(II) = .0
13      H(II) = .0
        RI(II)= RADII(NBODY + 1)
C
C**CALCULATE THE DIMENSIONLESS RADIUS RII
        DO 16 I=1,II
16      RII(I) =  (RI(I) - RADII(1))/(RADII(NBODY+1) - RADII(1))
        RETURN
        END
        SUBROUTINE SOLVE (IIM1,IIM2,II,NBODY,BETA,TAUT)
        DIMENSION GE(150),FE(150),DE(150),BETA(10),BE(150), BI(150)
        COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
C
C**CORRECT THE BODY CONDUCTANCES FOR VARIABLE CONDUCTIVITIES
1       DO 3  J=1,NBODY
        IB = IBODY(J,1)
        IE= IBODY(J,2) - 1
        DO 3  I=IB,IE
3       HX(I) = H(I)*(1. + BETA(J)*(T(I) + T(I+1))/2.)
C
C**START OF ELIMINATION -- CRANK-NICOLSON ALGORITHM
        DO 9 I=2,IIM1
        C1 = HX(I) + HX(I-1)
        BE(I) = CX(I) + C1
9       BI(I) = CX(I) - C1
        GE(2) = BE(2)
        FE(2) = (BI(2)*T(2) + HX(2)*T(3) + HX(1)*T(1)*2.)/GE(2)
        DO 5 I=3,IIM1
        DE(I) = -HX(I-1)/GE(I-1)
        GE(I) = BE(I) + HX(I-1)*DE(I)
5       FE(I) = (HX(I)*T(I+1) + HX(I-1)*T(I-1) + BI(I)*T(I) + HX(I-1)*
      2 FE(I-1))/GE(I)
        FE(IIM1) = FE(IIM1) + HX(IIM1)*T(II)/GE(IIM1)
C
C**BACK SUBSTITUTION
        T(IIM1) = FE(IIM1)
        DO 7 I=2,IIM2
        J = II - I
7       T(J) = FE(J) - DE(J+1)*T(J+1)
        RETURN
        END
        SUBROUTINE RESULT(TAUT,IIM1,II,TNUM,TDENCM,DZ,NBODY,QSTR,DETM,
      2  SQSTR,ENBL,      IIP1,SQIN,SQOUT,TIME)
        DIMENSION TSTAR(150),XM(10),                    Y(500)
        COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
        COMMON /BLK2/ RADII(11),NODES(10),XKZ(20),BETA(10),CP(20),RHO(20),
      2EMISS,RHOZ,CPZ,XKRZ,BDYR(11),RI(150),RII(150),DR(10)
C
C**CALCULATE DIMENSIONAL TIME,HEAT FLOWS PER UNIT DEPTH, TSTARS, M'S
C**AND WEIGHTED AVERAGE TEMPERATURE.  PRINT THESE QUANTITIES.
         CALL TAVE(II,IIP1)
         TSEC  = DZ**2 * RHOZ* CPZ * 3600./ XKRZ
        TIME = TAUT * TSEC
        QIN = HX(1)*XKRZ*6.2832*(T(1) - T(2))
        QOUT = HX(IIM1)*XKRZ*6.2832*(T(IIM1) - T(II))
        PRINT 100, SQIN, SQSTR, SQOUT, ENBL
                                  0
```

```
  100 FORMAT(5X, 11H QIN SUM = ,E12.4, 5X, 15H QSTORED SUM = , E12.4,5X,
     1  12H QOUT SUM = , E12.4/ 35X, 20H ENERGY BALANCE % = , E12.4)
      PRINT 31,TSEC,TAUT,TIME
   31 FORMAT(/7H TSEC =,E12.5,9H   TAUT =,F12.5,9H   TIME =,E12.5/)
      DO 1 I=1,IIP1
1     TSTAR(I) = (T(I) - TNUM)/TDENOM
      WRITE(6,5) TAUT
5     FORMAT(////22H0 DIMENSIONLESS TIME =,F7.3,10X28HHEAT FLOW PER FT (
     2BTU/HR-FT))
      WRITE(6,7) TIME,QIN,QOUT
7     FORMAT(22H  REAL TIME (SECONDS)=,E11.3,3X4HQIN=E12.3,7H  QOUT=,E12
     2.3)
C
C**PRINT THE DIMENSIONAL TEMPERATURES
      WRITE(6,11) T(1),IIM1,(T(I),I=2,IIM1)
11    FORMAT(  /35H0THE DIMENSIONAL TEMPERATURES ARE  /6H T(1)=,F10.2/
     213H T(2) THRU T(,I3,9H)  FOLLOW/(5F10.2,5X,5F10.2))
      WRITE(6,13)II, T(II), T(IIP1)
13    FORMAT(3H T(,I3,2H)=,F12.2,6X,7HT(AVE)=,F12.2)
      RETURN
      END
      SUBROUTINE TAVE(II,IIP1)
      COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
C
C**CALCULATE WEIGHTED AVERAGED TEMPERATURE AND STORE IT IN T(IIP1)
      SUM = .0
      SUM2 = .0
      DO 39 I=1,II
      SUM = SUM + C(I)*T(I)
39    SUM2 = SUM2 + C(I)
      T(IIP1) = SUM/SUM2
      RETURN
      END
      SUBROUTINE CHANGE (NBODY,TSEC,TAUT,II,IX,NNN,NMN,NIB,NIC)
      DIMENSION HZ(11),N1(11),N2(11)
      COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
      COMMON /BLK2/ RADII(11),NODES(10),XKZ(20),BETA(10),CP(20),RHC(20),
     2EMISS,RHOZ,CPZ,XKRZ,BDYR(11),RI(150),RII(150),DR(10),A(9),ITB(11)
C
C     J     = NUMBER OF R'S WHICH ARE TEMP. OR TIME DEPENDENT
C     N1(J)= RESISTOR NUMBER -- N1(J) = J1
C     N2(J)= RESISTOR TYPE
C     HZ(J)= RESISTOR'S INITIAL VALUE
C     A     = ARRAY CONTAINING COEFFICIENTS FOR FUNCTIONS, EXPONENTS ETC.
C     TSEC = CONVERSION FACTOR (REAL TIME IN SECONDS = TIMEX*TSEC)
C     EXPO1= EXPONENT N WHERE H = HZ*ABS(T(J1) - T(J1+1))**EXPO1
C     ITB  = ARRAY CONTAINING TYPE KEY FOR ALL BOUNDARY RESISTORS
C     TYPE = 1  H = CONSTANT
C     TYPE = 2  H = HZ*F3(TIME)
C     TYPE = 3  H = HZ*(DT)**EXPO1
C     TYPE = 4  H = HR + HC
C     TYPE = 5 H = HZ*F5(TIME) -- F5 IS A PERODIC RECTANGULAR WAVE
C
C  STORE INITIAL VALUES AND DETERMINE WHICH RESISTORS ARE NOT OF TYPE 1
      NIB1=NIB+1
      NIC1=NIC+1
      IF(NMN.EQ. NIC) NMN=0
      IF(TAUT.GT..0) GO TO 1
      N=0
      NMN=0
      N8 = IFIX( A(8) )
```

NOT REPRODUCIBLE

```
      N9 = IFIX( A(9) )
      T1 = T(1)
      T11 = T(11)
      HR = EMISS*.1714E-8/XKR2
      EXPO1 = A(7)
      J = 0
      IF(ITB(1).EQ.1) GO TO 7
      J = 1
      N1(1) = 1
      N2(1) = ITB(1)
      HZ(1) = HX(1)
    7 DO 5 I=1,NBODY
      IF(ITB(I+1).EQ.1) GO TO 5
      J = J + 1
      N1(J) = IBODY(I,2)
      N2(J) = ITB(I+1)
      J1 = N1(J)
      HZ(J) = HX(J1)
    5 CONTINUE
C
C**POINT OF ENTRY FOR TIME.GT.ZERO -- CALCULATE NEW BDY TEMPERATURES
C
C
    1 TIME = TAUT*TSEC
      T(11) = T11*(1. + TIME*(A(3) + A(4)*TIME))
C
C**IF ALL R'S ARE CONSTANTS RETURN OTHERWISE RECALCULATE THOSE CHANGING
      IF(J.EQ.0) RETURN
      DO 11 I=1,J
      J1 = N1(I)
      DTEMP = ABS(T(J1)-T(J1+1))
      IF(DTEMP.EQ..0) DTEMP=1.
      M = N2(I)
      GO TO (11,12,13,14,15),M
   12 HX(J1) = HZ(I) *(1. + A(5)*SIN(A(6)*TIME))
      GO TO 11
   13 HX(J1) = HZ(I)  *     DTEMP          **EXPO1
      GO TO 11
   14 TA = T(J1) + 460.
      TB = T(J1+1) + 460.
      HX(J1) =  HR*R1(J1)    *(TA**2 + TB**2)*(TA + TB)
     2  + HZ(I) * DTEMP ** EXPO1
      GO TO 11
   15 IF(NMN.LT. NIB1) HX(J1)= HZ(I)
      IF(NMN.GT. NIB .AND. NMN.LT. NIC1) HX(J1) = HZ(I) * A(5)
      IF(N.EQ.N9) N =-1
      N = N + 1
      NMN=NMN+1
   11 CONTINUE
      NN1 = NNN + 1
      IF((MOD(NN1,IX).NE.0).OR.(J.EQ.0)) RETURN
      DO 21 I=1,J
      J1 = N1(I)
   21 T(11+I+1) = HX(J1) * XKR2 / R1(J1)
      RETURN
      END
      SUBROUTINE XKKS(I,XK)
      COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
      TT=T(I)
      IF(TT-1472.) 10,10,14
   10 XK=28.30-.00870*TT
```

NOT REPRODUCIBLE

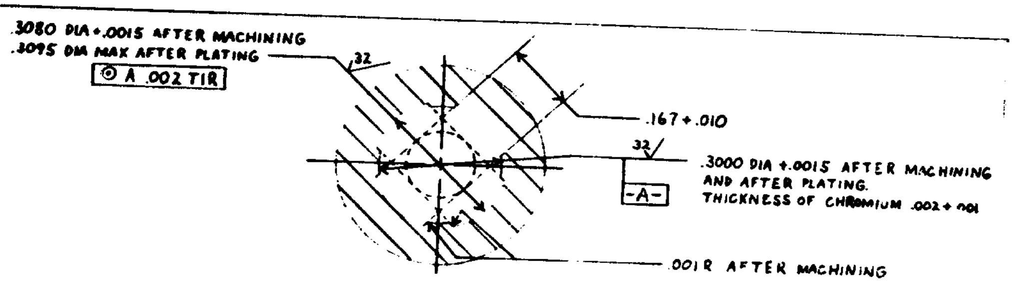
```
      GO TO 20
   14 XK=10.39+.00347*TT
   20 CONTINUE
   30 RETURN
      END
      SUBROUTINE LINEAR(A,X,Y,VV,I)
      DIMENSION X(20),Y(20)
    1 IF(Y(I+1) .LT. Y(I)) GO TO 100
C         USE FOLLOWING IF AS Y INCREASES X INCREASES
   10 IF(A-X(I))3,2,2
C         USE FOLLOWING IF AS Y INCREASES X DECREASES
  100 IF(A-X(I))2,2,3
    2 I=I+1
      GO TO 1
    3 I=I-1
      VV=Y(I)*(A-X(I+1))/(X(I)-X(I+1))+Y(I+1)*(A-X(I))/(X(I+1)-X(I))
      RETURN
      END
      SUBROUTINE TGHG(TOUTS,TOTS,AVGHG)
      TTS = TOUTS
C            RATIO = 3.268
      IF(TTS .LT. 359.2) TTS = 359.2
      AVGHG = .866956E-03 * TTS ** 2 - .62277   * TTS + 332.44
      TOTS = .1161224E-03 * TTS ** 2 - .44965   * TTS + 1606.35
      AVGHG = AVGHG + .20 * AVGHG
      TOTS = TOTS + .40 * TOTS
      RETURN
      END
      BLOCK DATA
C
C**INITIALIZATION OF LABELED COMMON TO DEFAULT VALUES
      COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
C
      COMMON /BLK2/ RADII(11),NODES(10),XKZ(20),BETA(10),CP(20),RHO(20),
C
     2EMISS,RHOZ,CPZ,XKRZ,BDYR(11),RI(150),RII(150),DR(10),A(9),ITB(11)
      DATA                          EMISS,RHOZ,CPZ,XKRZ,XKZ,BETA,CP,RHO/
C
     2                  1., 490.,.11, 10., 20*10., 10*.0,20*.11,20*490.0
C
     3 /,NODES,T,BDYR/10*5, 1.,149*.0,11*.0/,A,ITB/6*.0,.25,2*.0,11*1/
      END
```

APPENDIX C

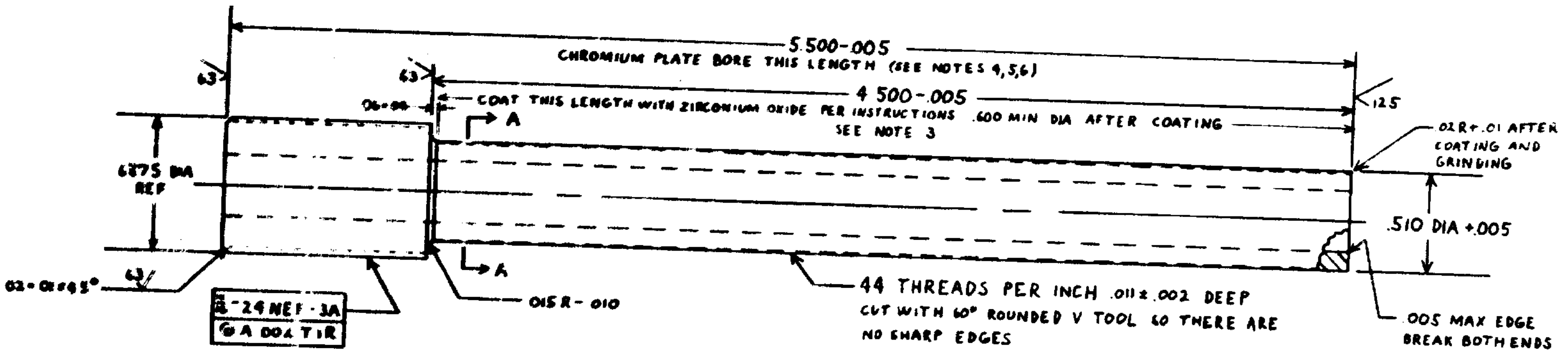
Modified M60 Gun Barrel Design Data

NOTES.

1 MATERIAL STEEL, SPEC MIL-S-11595 CHROMIUM-MOLYBDENUM-VANADIUM
2. HEAT TREATMENT BEFORE MACHINING, HEAT AT 1620°F±25°F. QUENCH IN AGITATED OIL. TEMPER TO HARDNESS SPECIFIED.
3 FINAL DIAMETER WILL BE OBTAINED BY GRINDING COATED SURFACE FOR A SHRINK FIT OF .0002 TO .0010 IN FRONT BARREL 140299 SEE BARREL SUB-ASSEMBLY 140301 SURFACE WILL BE ◎ A .002 TIR AFTER GRINDING.
4. REMOVAL OF MATERIAL AFTER MACHINING BUT PRIOR TO CHROMIUM PLATING SHALL BE ACCOMPLISHED BY ELECTROPOLISHING.
5 CHROMIUM PLATE, FED SPEC QQ-C-320 CLASS 2
6 NO MECHANICAL METHODS FOR REMOVAL OF CHROMIUM PLATE ARE PERMITTED IN THE BORE.

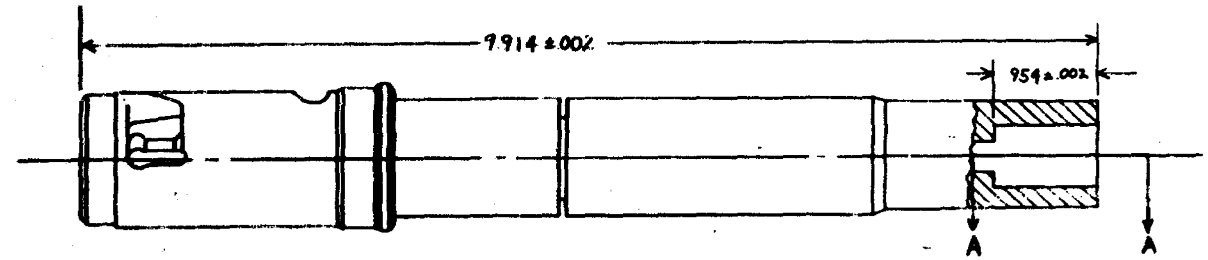


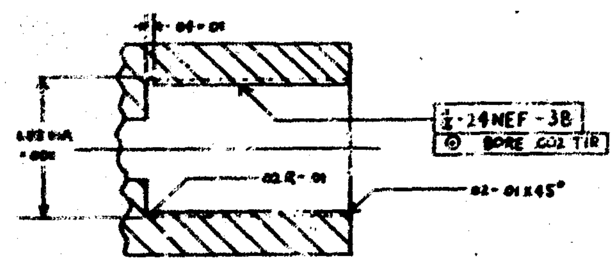
SECTION A-A SCALE 4/1
RIFLING: 4 GROOVES, 1 TURN IN 12 INCHES RH



37

M60 HEAT TRANSFER STUDY 7 DRAWINGS	AMSWE-RET-ED USA WECOM, ROCK ISLAND, ILL.		
ENGINEER: P.A. Lynch 11 June 70	COATED LINER		
CHECKER: B.E. Hoffgaard 29 June 70		SIZE B	140297
APPROVAL: Walter Wahl 29 June 70	SCALE 2/1		SHEET 1 OF 1



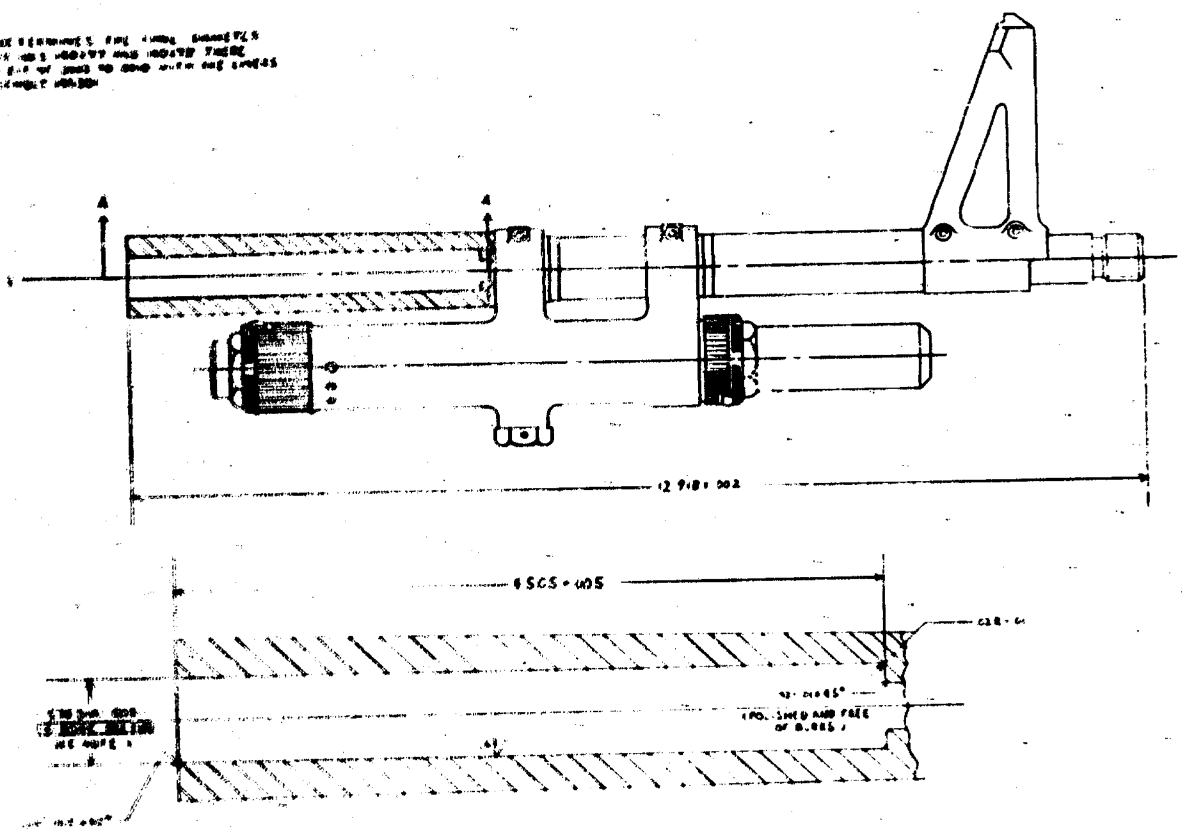


SECTION A-A
SCALE 2/1

35

M60 HEAT TRANSFER STUDY.	AMSWE-RET-ED
7 DRAWINGS	USA WECOM, ROCK ISLAND, ILL.
	BACK BARREL
ENGINEER: 11 June 70	
CHECKER: B L Hofgaard 29 June 70	SIZE B 140300
APPROVAL: 24 June 70 SCALE 1/1	SHEET 1 OF 1

NOTES:

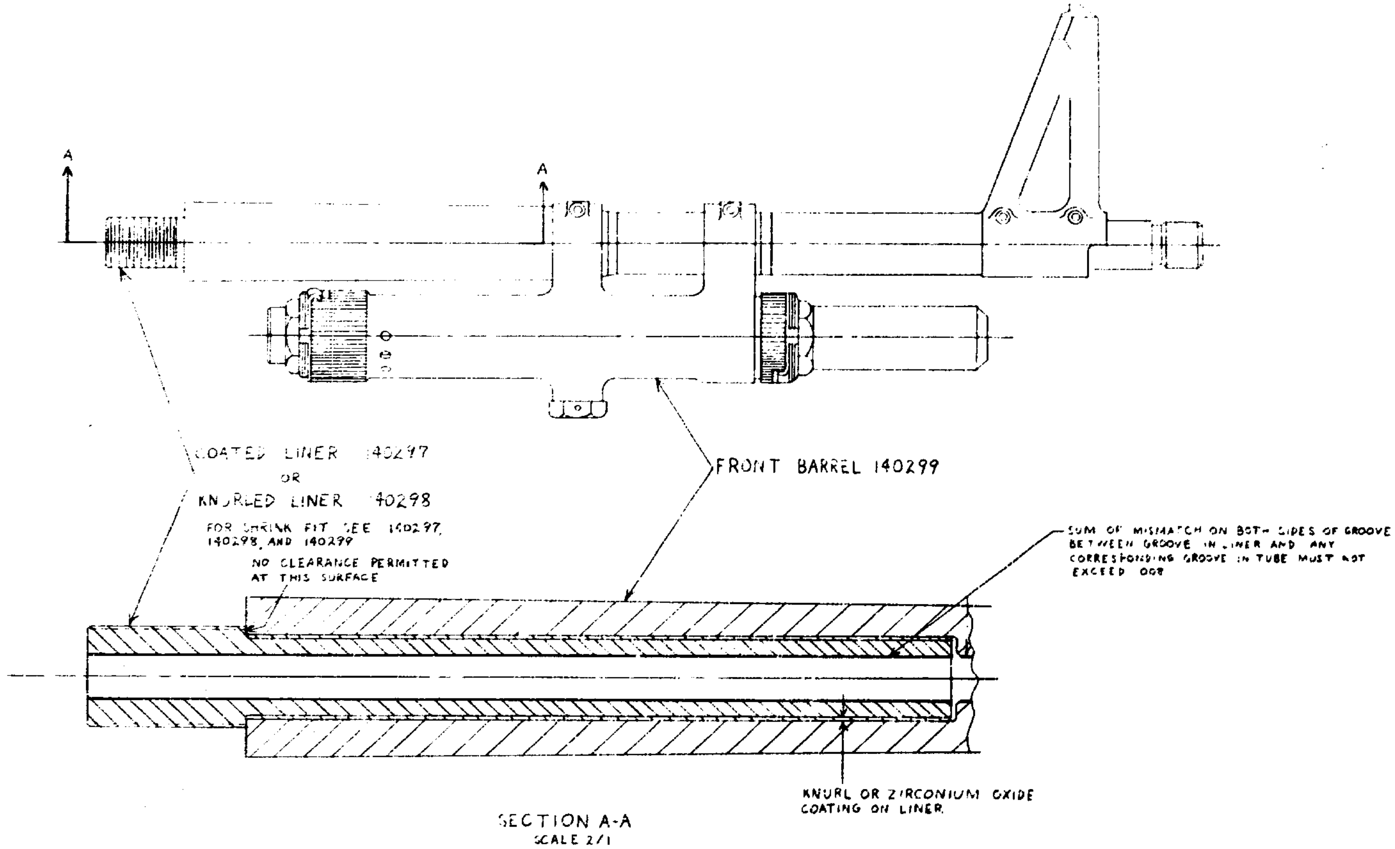


SECTION A-A
SCALE 2/1

M60 HEAT TRANSFER STUDY

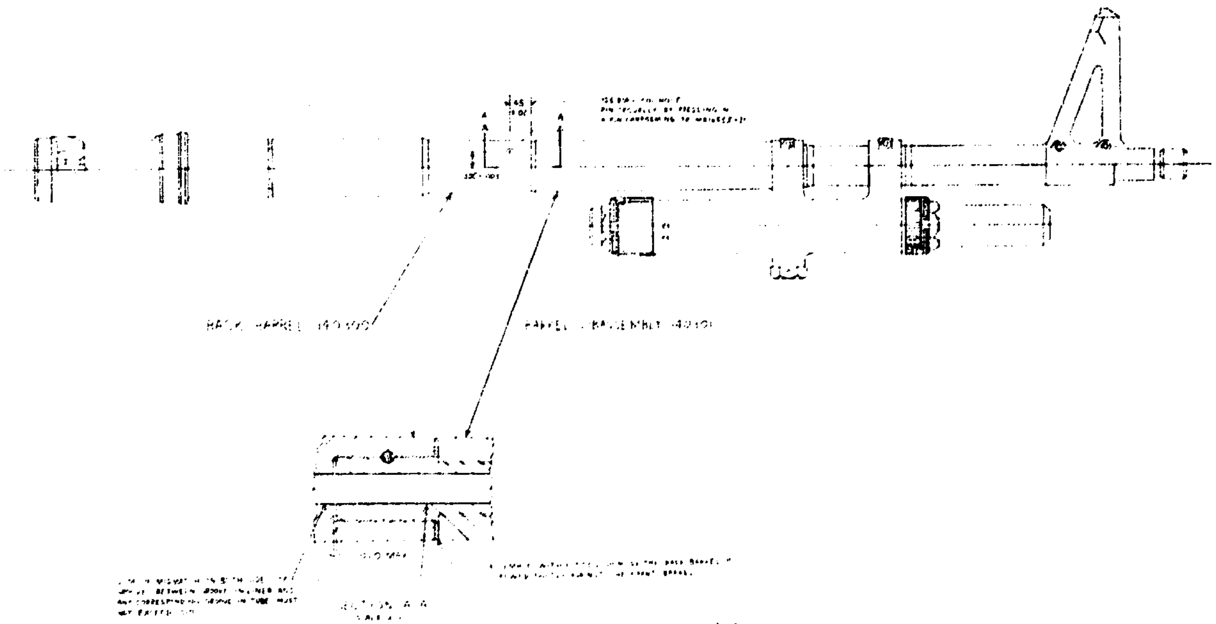
7 DRAWINGS

ENGINEER 12 June 70	AMSWE-RET-ED USA WECOM, ROCK ISLAND, ILL.	
CHECKER 29 June 70	FRONT BARREL	
APPROVAL 29 June 70	SIZE C	140299
SCALE 1/1		SHEET 1 OF 1



4C

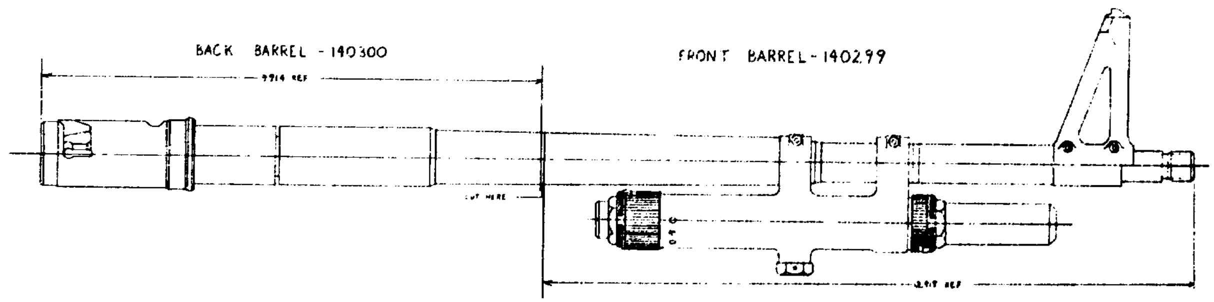
M60 HEAT TRANSFER STUDY 7 DRAWINGS	AMSWE-RET-ED USA WECOM, ROCK ISLAND, ILL.		
ENGINEER D. Lynch 12 June 70	BARREL SUB-ASSEMBLY		
CHECKER B. E. Hoglund 29 June 70		SIZE C	140301
APPROVAL [illegible] 29 June 70	SCALE 1/1		SHEET 1 OF 1



41

BARREL ASSEMBLY

NOTES
MATERIAL
A.I.E. PART NO 7269528
FED STOCK NO 1005-678-6202



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M60 HEAT TRANSFER STUDY	ARMSWEAP-ED USA WECOM ROCK ISLAND, ILL.
	M60 HEAT TRANSFER BARREL
	D 40304

AD____________ Accession No.____________
U. S. Army Weapons Command
Research, Dev. and Eng. Directorate
Rock Island, Illinois 61201

CONDUCTIVE HEAT-TRANSFER RESISTANCE OF COMPOUND BARREL INTERFACE, by Darrel M. Thomsen and Alexis B. Zavoico, CPT, U. S. Army

Report RE TR 71-36, Jun 71, 47 p. incl. illus. tables, (DA Project 1T061101A91A, AMS Code 501A.11.844) Unclassified report.

This is a continuation of a heat-transfer investigation performed as In-House Laboratory Independent Research to determine the effect of interface thermal-resistance on multilayer gun barrel radial temperature distributions.

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2. Heat transfer (conduction)
3. Multilayer gun barrel
4. Ceramics

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CONDUCTIVE HEAT-TRANSFER RESISTANCE OF COMPOUND BARREL INTERFACE, by Darrel M. Thomsen and Alexis B. Zavoico, CPT, U. S. Army

Report RE TR 71-36, Jun 71, 47 p. incl. illus. tables, (DA Project 1T061101A91A, AMS Code 501A.11.844) Unclassified report.

This is a continuation of a heat-transfer investigation performed as In-House Laboratory Independent Research to determine the effect of interface thermal-resistance on multilayer gun barrel radial temperature distributions.

(Cont.) over

UNCLASSIFIED

1. Thermal interface resistance
2. Heat transfer (conduction)
3. Multilayer gun barrel
4. Ceramics

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